An Activation Model of Motor Response and H-Reflex under FES

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Abstract

In this work a model is presented that can improve the estimation of muscle activation under electrical stimulation. The model includes not only the motor recruitment but also the H-reflex recruitment, which is, at the lower stimulation levels, responsible for a larger exerted force than expected based on only motor recruitment. In the model it is assumed that recruitment curves are sigmoid shapes, that there is no difference between motor units and no specific recruitment order. The model is fitted to the measured recruitment curves of two healthy volunteers and shows good fits, with R^2 values above or around 0.95. The next goal is to use this improved activation model in combination with a force estimating muscle model in order to enhance the accuracy of the force estimation

1 Introduction

Functional electrical stimulation (FES) can provide a mean to restore human functions in various ways; pacemakers, cochlear implants and deep brain stimulation are just some examples. When the descending paths in motor control are lost, FES can provide a way to restore movement with the use of the bodies own actuators: the muscles. Given the highly complex and nonlinear nature of muscles, models have been developed to improve the performance of FES systems. Structure based models can predict the behaviour of the muscles and limbs as well as give meaningful parameters regarding the muscles of interest [1]. This model consists of several blocks representing different aspects of the stimulation: the activation, the mechanical behaviour and geometrical properties [1].

Control of the exerted force of a muscle under FES is often performed based on recruitment of increasing numbers of motor units, either rate coding is also possible but this is included in fewer models [2]. An accurate recruitment function is thus needed in the activation block of a structure based model. At this point one important phenomenon is not taken into account in the estimation of motor unit recruitment under FES: the presence of the Hoffmann reflex (H-reflex). The H-reflex is present at the lower stimulation intensities and produces a higher force than what would be expected based on the motor response. It makes the estimation of exerted force at the low stimulation intensities inaccurate and does not represent what is actually happening. This H-reflex also prevents from accurately identifying the recruitment curves.

This paper proposes a model for motor unit recruitment which does take into account the H-reflex and uses the EMG signal for the identification of both contributions: the H-reflex and the direct motor activation. This activation model can thus be used in the muscle model presented in [1]. Preliminary experiments show that this model enables to explain accurately the activation level measured and thus, in comparison with the conventional activation models, is able to predict more accurately the activation of the muscle induced by both phenomena.

2 Activation model

The activation model consists of separate functions to describe the motor recruitment and the H-reflex recruitment. It also describes the extinction of the H-reflex contribution with increasing motor response.

2.1 Motor and reflex recruitment

It is known that motor recruitment is well described by a sigmoid function. This accounts both for the relation between activation and stimulation amplitude as for the relation between activation and pulse width [3, 4]. Recently it has been shown that a sigmoid shape is also the best fit for the ascending part of the H-reflex recruitment curve [5]. The function to describe the sigmoid recruitment function has the following general shape:

$$A = \frac{c_1}{1 + \exp\left[c_2 \cdot (c_3 - s)\right]} \tag{2.1}$$

In this function A is the number of recruited motor units, s the stimulation input (amplitude or pulse width) and c_1, c_2 and c_3 constants that alter the plateau, steepness of the sigmoid and the stimulation needed for 50% recruitment respectively.

The descending part of the H-reflex recruitment curve is more complicated. The simplest explanation for the extinction of the H-reflex is that the reflexive activity is blocked by collisions with the antidromic action potentials induced in the motor neurons by the stimulation. This means that a function to describe the reflexive activation of motor units also requires the motor recruitment as an input.

Regarding the extinction of the H-reflex several assumptions have to be made in order to estimate the collisions: 1) There is a homogeneous motor unit pool. 2) A motor unit has an equal chance of being recruited in either the motor response or the H-reflex. 3) Motor recruitment and H-reflex recruitment are mutually independent.

Under these assumptions the expected portion of the motor units recruited in the H-reflex that collides with the motor response, can be calculated. With M and H the normalised number of motor units in the motor response and H-reflex respectively, the expected overlap between the motor recruitment and the H-reflex recruitment (COL) is given by:

$$COL = H \cdot M \tag{2.2}$$

The number of motor units activated in the H-reflex (H*) is than given by:

$$H^* = H - COL = H(1-M) \tag{2.3}$$

2.2 Structure of the activation model

The form in which the motor recruitment and H-reflex recruitment can be used in a model is given in Figure 1

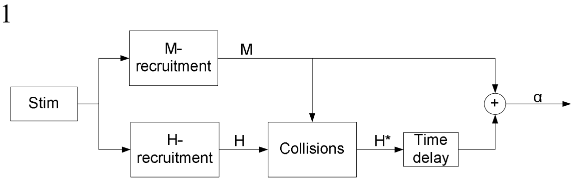

Figure 1 Structure of the activation model.

From the stimulation parameters (amplitude or pulse width) the motor response recruitment (M) and the H-reflex recruitment (H) are calculated. From this the portion of H that actually results in muscle contraction is calculated (H*). H* reaches the muscle slightly later than the direct motor response does, so a time delay is added. Finally the both pathways are added giving the activation (α) of the muscle as a result of the stimulation.

In the blocks the functions of equations (2.1) and (2.3) are implemented, the formulas to calculate the M and H* become:

$$M = \frac{1}{1+\exp\left[cm_2 \cdot (cm_3 - s)\right]} \tag{2.4}$$

$$H^* = \frac{ch_1}{1+\exp\left[ch_2 \cdot (ch_3 - s)\right]} \cdot (1-M) \tag{2.5}$$

With this model the activation that is used in the mechanical part of the muscle model will contain both the motor response activation and the H-reflex activation. Identification of the parameters of the recruitment functions can be achieved based on the amplitudes of the M-wave and the H-wave in the EMG signal.

3 Model identification

3.1 Method

Recruitment curves were determined for two subjects to test the proposed activation model.

Subjects were seated on a chair with their right foot fixed on a calibrated dynamometric pedal (Captels, St-Mathieu de Treviers, France). Transcutaneous stimulation was applied to the tibial nerve by bipolar electrodes. A cathode electrode was placed in the popliteal fossa, a 50 cm^2 anode electrode was placed on the knee at the patella. Stimulation was delivered in the form of rectangular monophasic pulses with durations of 200 μs by a constant current stimulator (DS7AH, Digitimer Ltd., Hertfordshire, UK). For EMG measurements bipolar surface Ag/AgCl-electrodes were placed on the muscle belly of the medial gastrocnemius. Signal acquisition of the force and differential EMG signal was done with a sample frequency of 2048 Hz by the Biopac MP100 (Biopac Systems, Inc., Santa Barbara, CA).

Single pulses were delivered with increasing amplitude in steps of 10 mA to identify the motor threshold and the maximum recruitment. From the maximum recruitment, stimulation amplitude was again reduced; this time in steps of 2 mA to get a higher resolution in the recruitment curve. The procedure was performed once.

From the EMG data the M-waves and H-waves were identified for all stimulation amplitudes. The amplitudes of both M-waves and H-waves were determined as the peak to peak amplitudes. All amplitudes were normalized to the maximal M-wave amplitude. Stimulation amplitude was normalised to the lowest stimulation amplitude needed to induce a maximal M-wave. For each simulation the peak force of the twitch was determined.

Using the MATLAB curve fitting toolbox the recruitment functions for motor response activation (M) and H-reflex activation (H*) are fitted to the measured M-wave and H-wave amplitudes. Normalised wave amplitude and normalised activation are assumed to be interchangeable. Goodness of fit is assessed based on the fraction variance accounted for (R^2).

3.2 Results

The recruitment curves of the motor response had the typical sigmoid shape for both subjects. The H-reflex recruitment curves showed the expected increase at the lower stimulation amplitudes, followed by a decrease when the motor response is getting larger.

Peak force increased with increasing stimulation amplitude. At the low stimulation amplitudes the force increases faster than what would be expected by looking at the motor recruitment curve. At these levels the H-reflex also contributes to the exerted force. This can be seen in Figure 2

The activation model was fitted to the data. The data and fitted recruitment curves are shown in Figure 3

As can be seen in the plot, the fitted function follows the measured data closely. This is also visible in the high R^2 values: The average R^2 value for the 4 fitted recruitment curves (motor recruitment and H-reflex recruitment for each subject) is 0.9731. For the motor response recruitment curves the average R^2 is 0.9916. For the H-reflex recruitment curves the average R^2 is 0.9545.

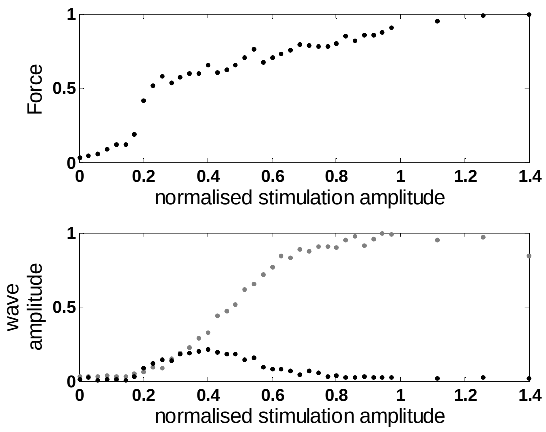

Figure 2 Normalised data of one of the subjects: peak force and wave amplitude. In the lower graph the black dots represent the H-wave. The peak force shows a strong increase just above the motor threshold.

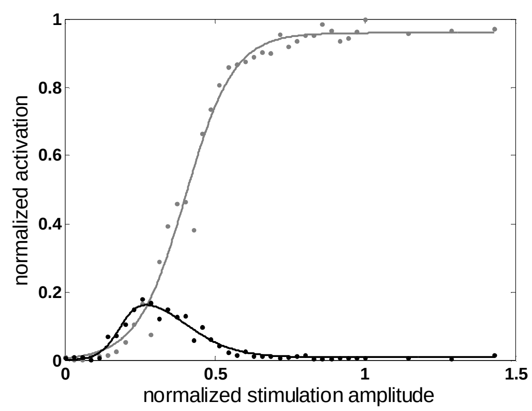

Figure 3 Recruitment curves fitted to the measured data of one of the subjects. The black line and dots represent the H-reflex.

4 Discussion

The aim of this study was to develop an activation model which can be used in combination with a structure based muscle model. Including not only the motor response in the activation but also the H-reflex is important because the H-reflex is responsible for most of the force at the lowest stimulation intensities. Not including the H-reflex in the activation will result in an underestimation of the exerted force at those stimulation intensities.

The model fits that are made using the proposed model follow the measured recruitment curves closely. Something which is also reflected in the high fraction variance accounted for in both the motor response recruitment curves and the H-reflex recruitment curves. From these fits it can be concluded that the proposed activation model can be used to give a better estimation of the muscle activation induced by electrical stimulation.

This activation model is based on some assumptions regarding the recruitment order and reason of the extinction of the H-reflex. Physiologically seen these assumptions may not be completely valid. But regarding the quality of the current model fits and the increase in model complexity that a more physiological recruitment order would mean, the assumptions made here can be justified.

Future work includes the testing of the proposed activation model in combination with the complete muscle model and comparing the force predictions with the new and the old activation model. The assumption is then that the new model should give a better force estimation especially at the low stimulation intensities when the H-reflex has the largest contribution to the exerted force.

5 Literature

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